Spectral Bluing and Space Weathering on Asteroids

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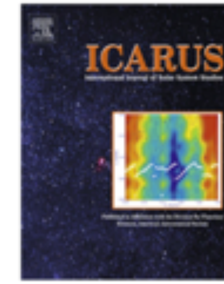

Spectral bluing induced by small particles under the Mie and Rayleigh regimes

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ABSTRACT

Scattering by particles significantly smaller than the wavelength is an important physical process in the icy and rocky bodies in our Solar System and beyond. A number of observations of spectral bluing (referred to in those papers as 'Rayleigh scattering') on planetary surfaces and cometary comas have been recently reported, however, the necessary mathematical modeling of this phenomenon has not yet achieved maturity. This paper is a first step to this effect, by examining the effect of grain size and optical index on the albedo of small conservative and absorbing particles as a function of wavelength. The conditions necessary for maximization of spectral bluing effects in real-world situations are identified. We find that any sufficiently narrow size distribution of scattering particles will cause spectral bluing in some part of the EM spectrum regardless of its optical index. We also investigate the effect of including a distribution of particle sizes.

Three takeaways

1. Spectral bluing occurs for particles in contact with each other, not just atmospheric molecules and aerosols
2. We can estimate the grain sizes of these particles
3. This process may explain spectral bluing on C and B class asteroids (e.g. 101955 Bennu) and may be spatially constrained using OSIRIS Rex.

Takeaway 1.

Spectral bluing occurs for

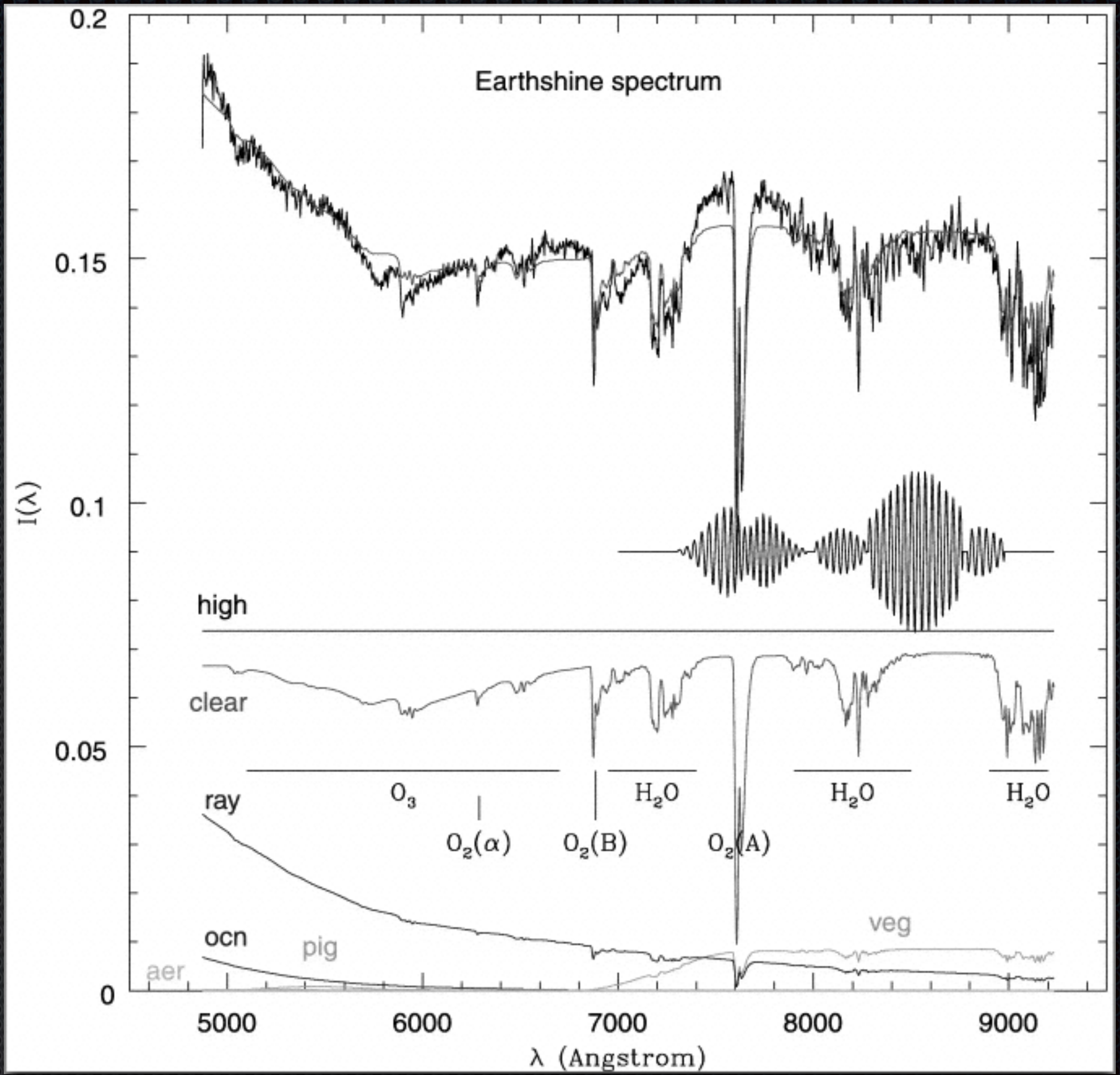
particles in contact with each other,

not just atmospheric molecules and aerosols

"Ray" λ^{-4}

"Aer" $\lambda^{-1.3}$

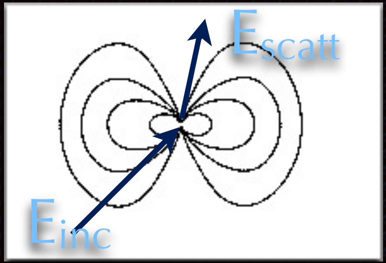
-1.3 is Angstrom's [1929] exponent, varies from 2 for small "fresh" smoke to 0 for coarse 2 micron sand



Earthshine spectrum using Seward Observatory. 2.3m

Ref: Woolf et al. (2002) *ApJ* 574 430

Take away 1. Spectral bluing occurs for close packed particles ...



$$P \sim p e^{-ikt}$$

dipole moment P is an oscillating function of time

$$\ddot{P} \sim k^2 P$$

second time derivative of dipole moment

$$E_{inc} = E_0 e^{-ikt}$$

E_{inc} is incident electric field

$$E_{scatt} \sim \frac{\ddot{P}}{r} (\hat{n} \times P) \times \hat{n} = k^2 p \sin\gamma \frac{e^{-ikt}}{r}$$

E_{scatt} is scattered electric field which depends on the accel. of dipole moment and has 1/r dependence in radiation zone

$$I_0 = \frac{c}{8\pi} |E_0|^2$$

$$I = \frac{c}{8\pi} |E_{scatt}|^2$$

Scattered (I) and incident (I_0) intensity from Poynting vector in Gaussian units

$$W = \frac{1}{3} k^4 c |p|^2$$

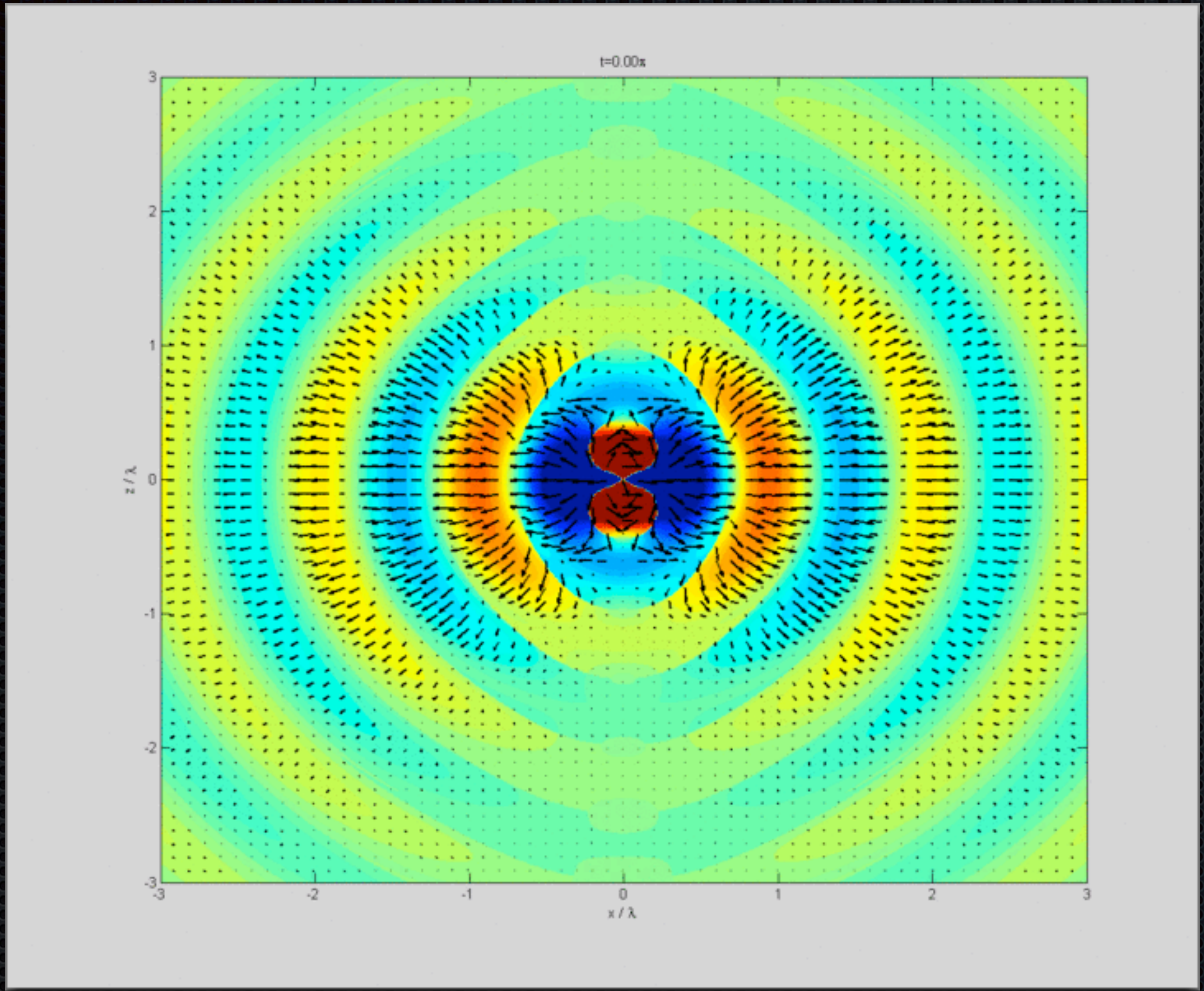
Integrate the scattered intensity over a sphere

$$C_{sca} = \frac{W}{I_0} = \frac{8\pi}{3} k^4 |\alpha^2|$$

scattering cross section is scattered intensity over incident intensity

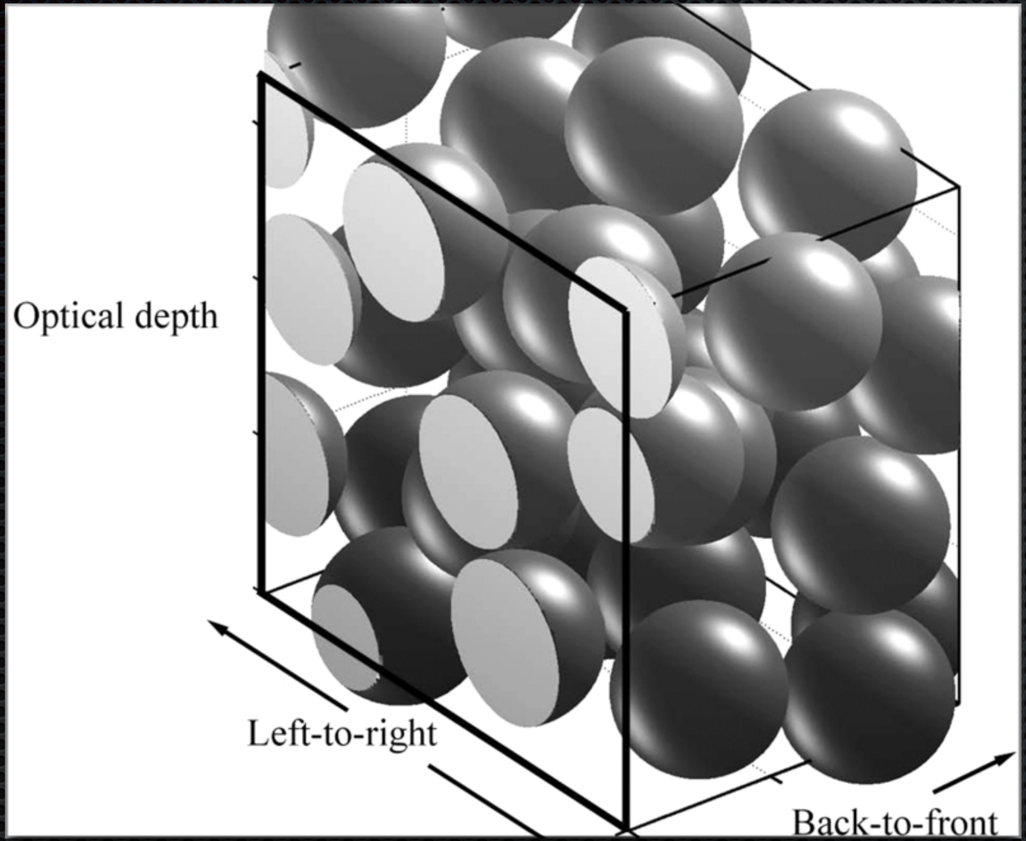
Intuitive "Derivation" of scattering by Spherical Dipole

Ref: van de Hulst (1957) *Light scattering by small particles*



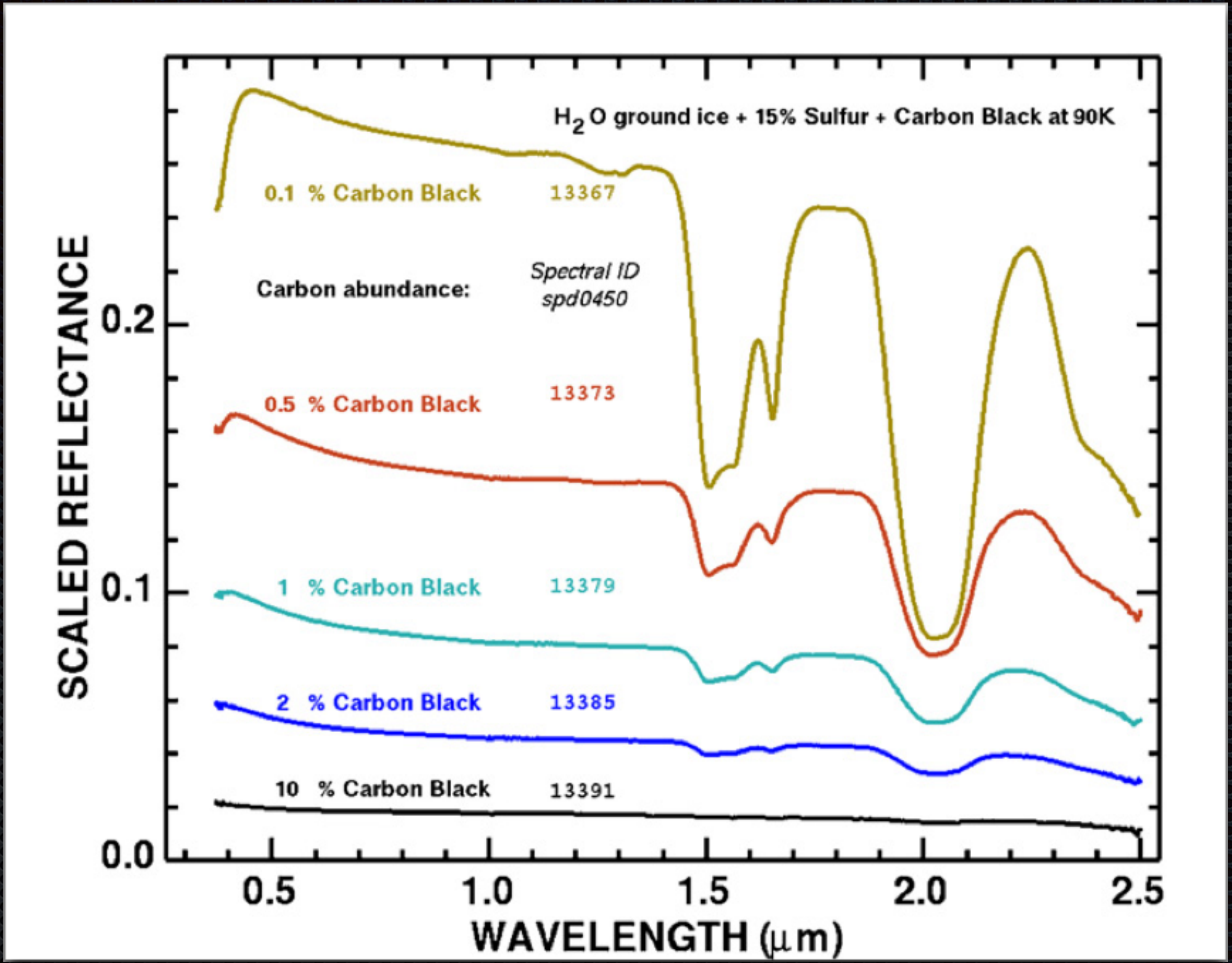
Dipole radiation (single tuning fork analogy)

Ref: *Wikipedia Commons*



What happens when the dipoles are packed close together?

Does Spectral Bluing still occur?



Laboratory Spectral bluing when carbon black added to ice

Ref: Clark et al. (2008) *Icarus* **193** *Fig. 12b (carbon black d=0.2 microns*

Clark et al. (2012) *Icarus* **218** 831-860

Take away 1. Spectral bluing occurs for close packed particles …

Take away 2.

We can estimate the size of these particles …

$m = n + i\kappa$

$$w = \frac{Q_{sca}}{Q_{ext}} = \frac{Q_{sca}}{Q_{sca} + Q_{abs}}$$

$$C_{sca} = \frac{8\pi}{3}k^4\left|\frac{m^2-1}{m^2+2}\right|^2 a^6 = \frac{8}{3}X^4\left|\frac{m^2-1}{m^2+2}\right|^2 a^2\pi$$

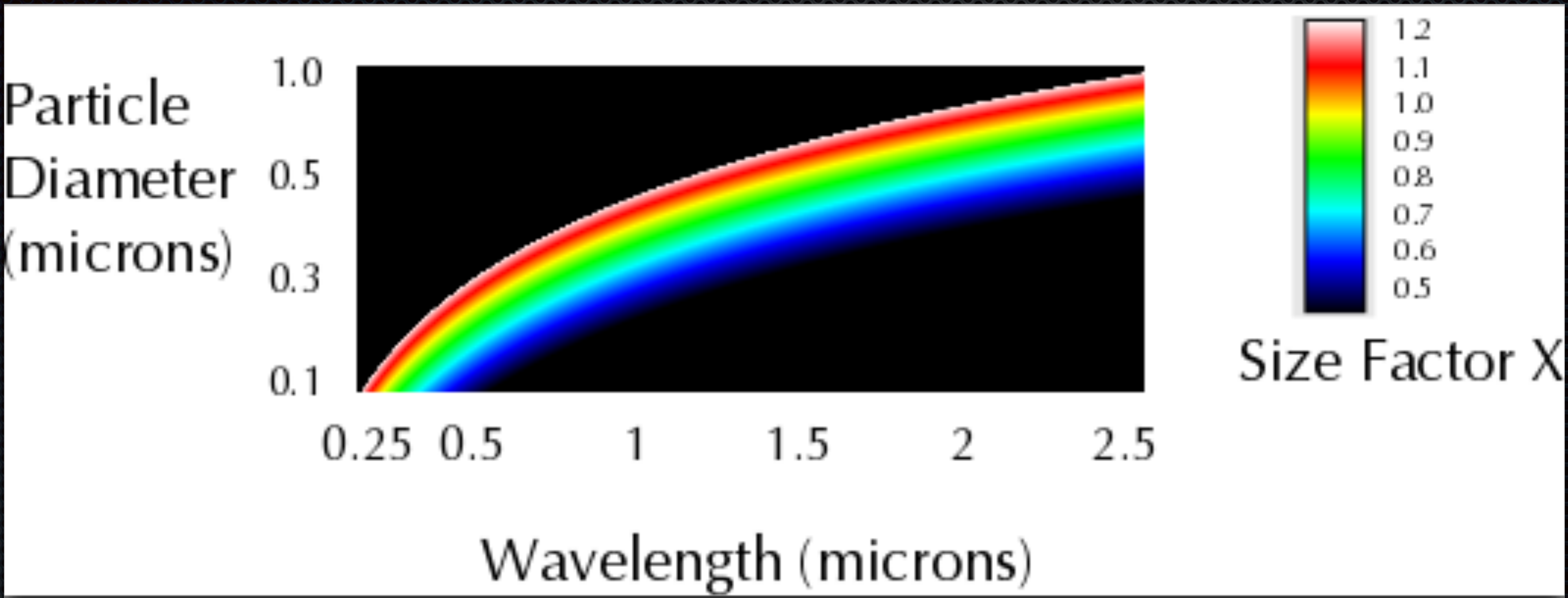
$$C_{abs} = 4\pi k \mathrm{Im}\left(\frac{m^2-1}{m^2+2}\right)a^3 = -4X\mathrm{Im}\left(\frac{m^2-1}{m^2+2}\right)\pi a^2$$

$$w(X,n,\kappa) = \frac{X^3((n-1)^2+\kappa^2)((n+1)^2+\kappa^2)}{X^3((n^2+\kappa^2)^2-2(n^2-\kappa^2)+1)+9\kappa n} \qquad (12)$$

$$\frac{dw}{dX}(X,n,\kappa) = \frac{X^2(27\kappa n((n-1)^2+\kappa^2)((n+1)^2+\kappa^2))}{(X^3((n^2+\kappa^2)^2-2(n^2-\kappa^2)+1)+9\kappa n)^2} \qquad (15)$$

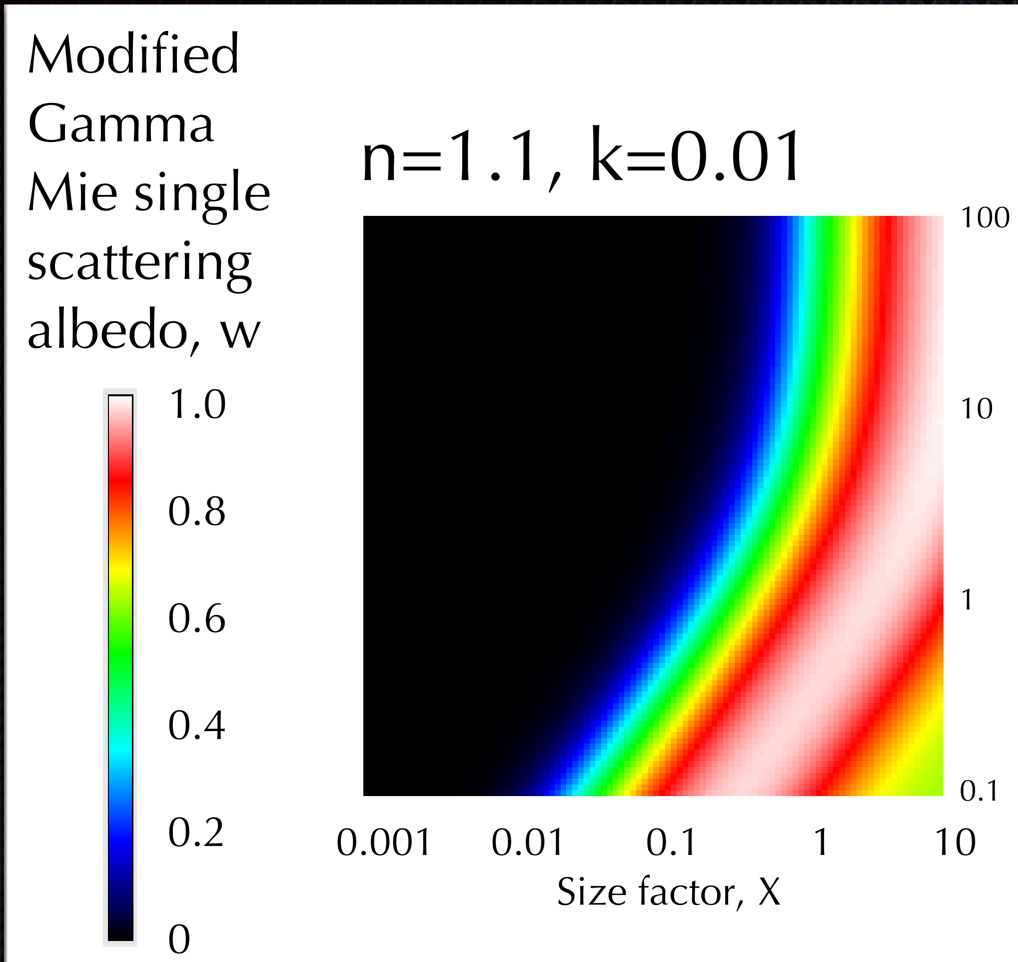
Formula for Rayleigh albedo and derivative with wavelength

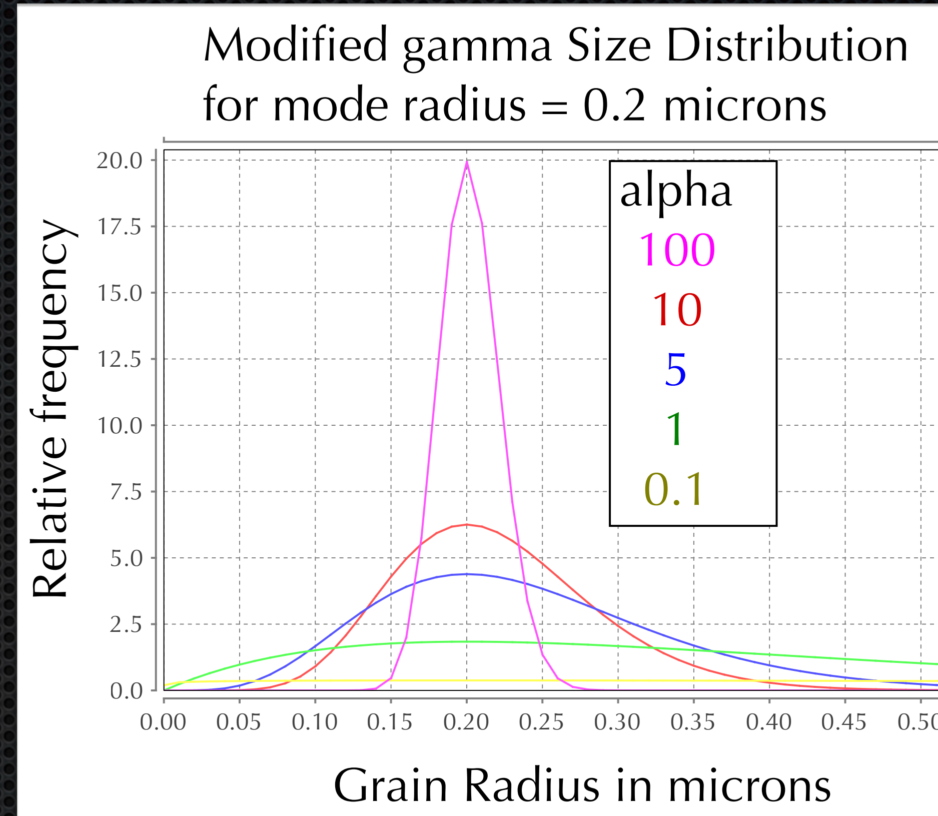
Ref: Brown (2014) *Icarus, Eqns (12,15)*



Estimate of grain size from spectral bluing

Ref: Brown (2014) *Icarus, Figure 7*





$$n(r) = Cr^{\alpha}e^{-\frac{\alpha r}{r_m}}$$

Effect of a size distribution on spectral bluing

Ref: Brown (2014) *Icarus, Figure 6a and b* *(symmetrical modified gamma size dist, critical size dispersion of 5, for this dist 0.2+/- 0.1 microns or std dev. of 0.1)*

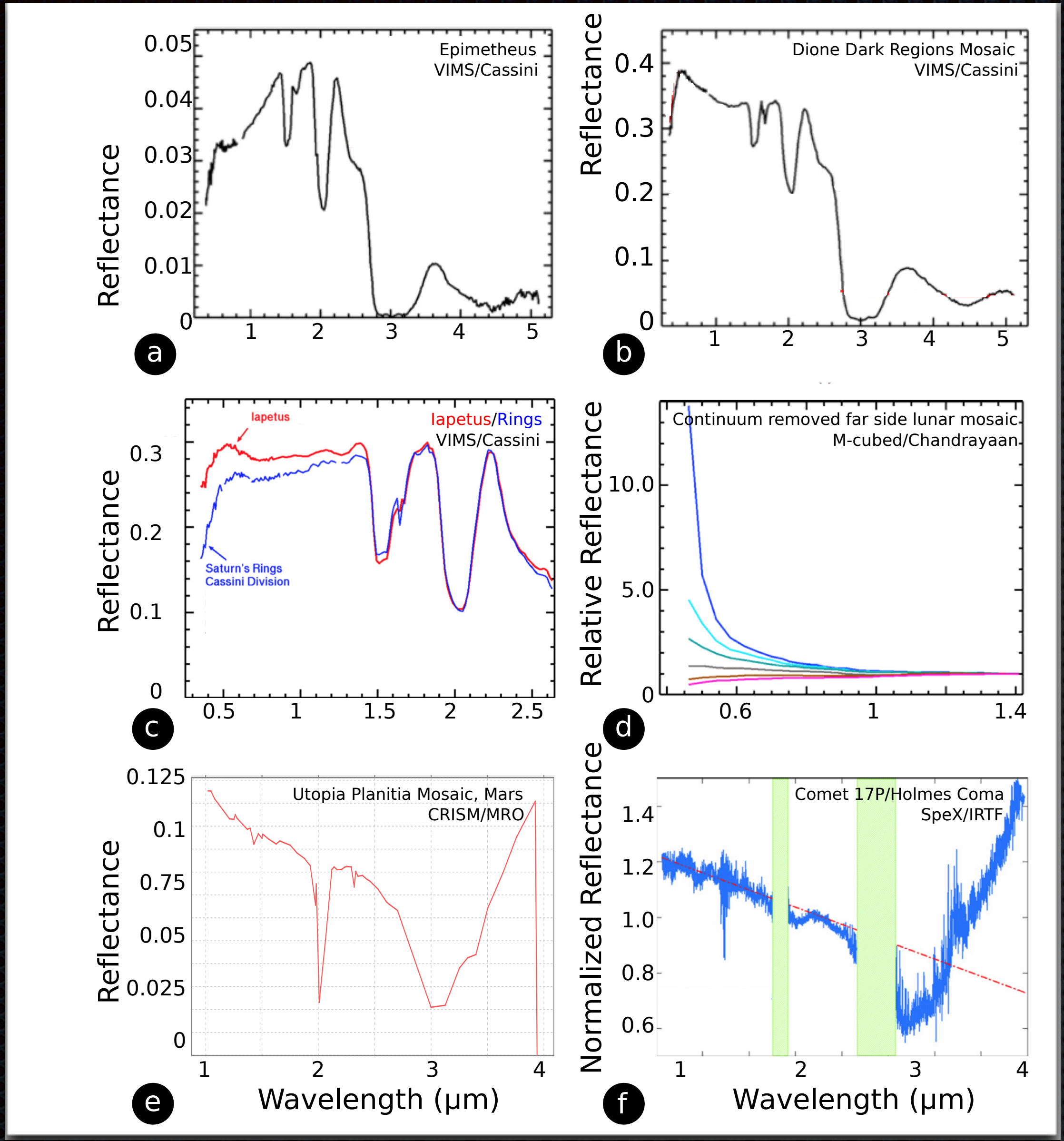
Take away 2. We can estimate the size of these particles ...

Take Away 3.

This process may explain spectral bluing on C and B class asteroids (e.g. 101955 Bennu) and may be spatially constrained using OSIRIS Rex.

Average (min-max) inferred grain size (microns)

Epimetheus	0.2 (0.05-0.4)
Dione	0.3 (0.1-0.5)
Moon	0.3 (0.1-0.5)
Rings/Iapetus	0.2 (0.05-0.4)
Mars	0.5 (0.3-0.8)
Holmes	0.5 (0.3-0.8)



Rogues Gallery of Solar System Spectral Bluing

Ref: Brown 2014 *Icarus*, Figure 8

Meteorite spectra show spectral bluing

Ref: Clarke et al. (2011) *Icarus*

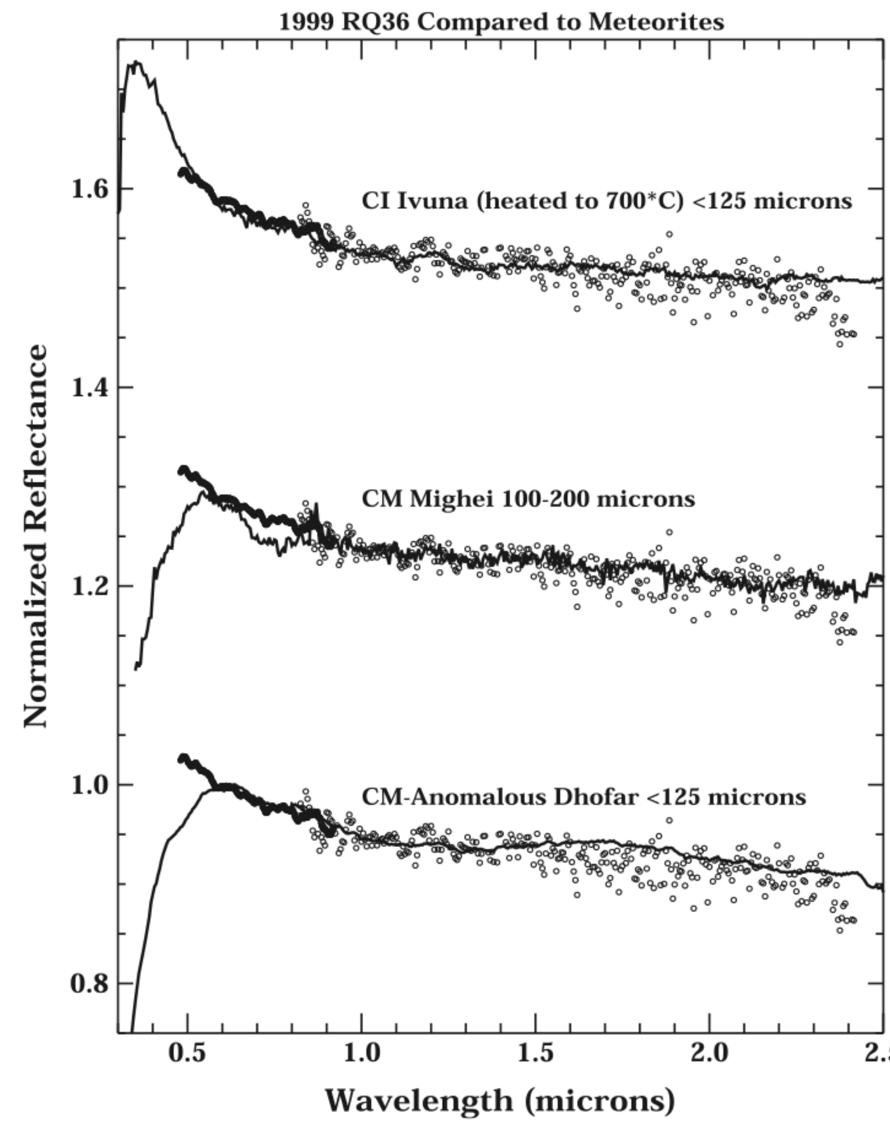


Fig. 3. Asteroid 1999 RQ36 is compared to the best match meteorite spectra found in a least-squares search through the RELAB database. Asteroid data are shown in small circles (for the visible wavelengths there are so many channels that the small circles merge into a thick line). Meteorite data are continuous (thin) lines.

Comet Harley 2 observed by EPOXI (see also LADEE UVS from Cook et al *this meeting*)

Ref: A'Hearn et al. (2011) *Science*

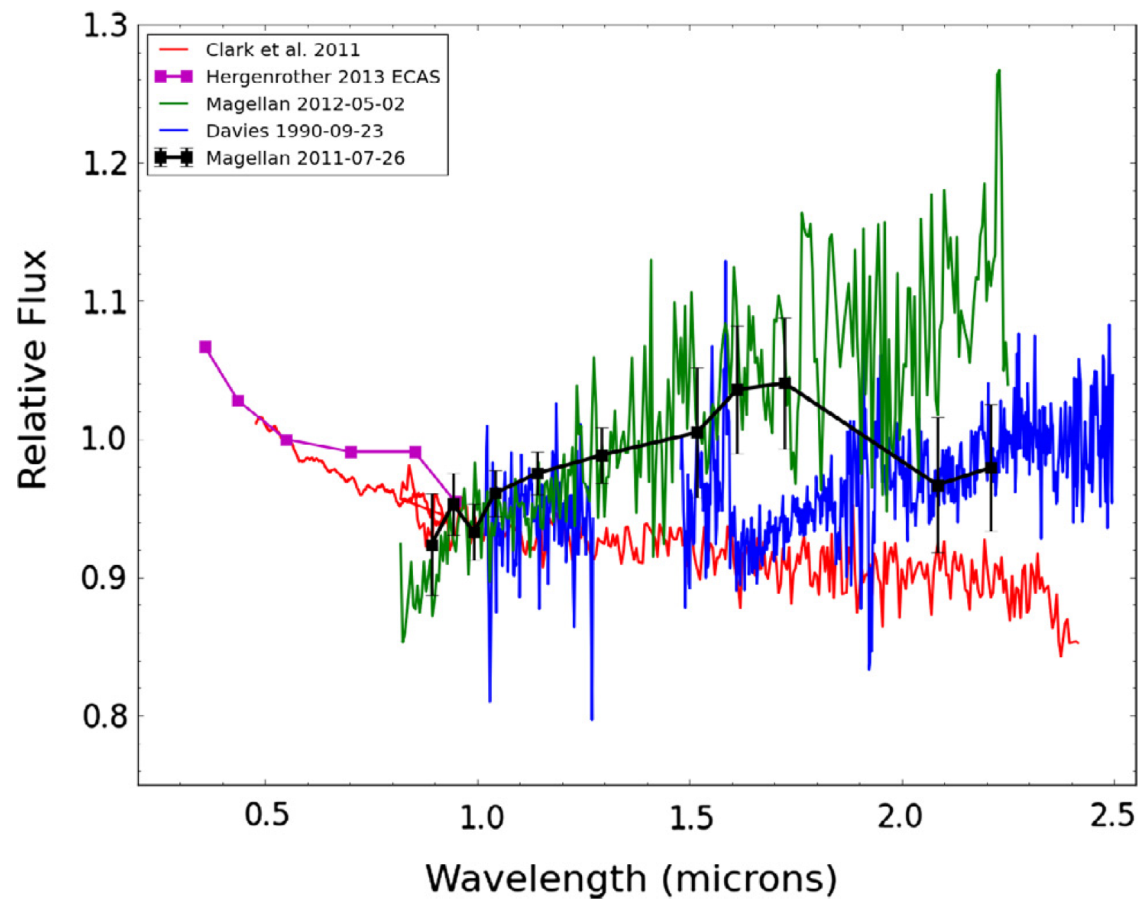


Fig. 2. New spectral measurements of Bennu (Magellan data) relative to previous measurements presented by Clark et al. (2011) and Davies et al. (2007). All spectra fall within the broad category of "C-complex" asteroids, with the negative spectral slope falling within the sub-class denoted as "B-type." All spectra are also compatible with the range of spectral characteristics for carbonaceous chondrite meteorites.

101955 Bennu observations from 1999,2005 and 2012

Refs: *Clark et al. 2011, Hergenrother et al. 2013, Binzel et al. 2015 "finer grained regolith near equator" due to red slope from 0.8-2.3 microns*

Take away 3. This process may explain asteroid spectral bluing ...

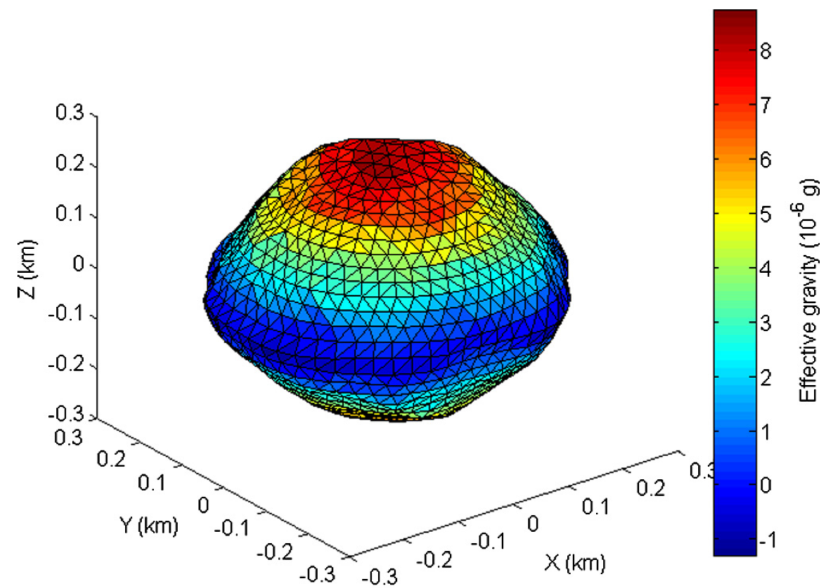


Fig. 9. Effective surface gravity map of (101955) Bennu at a rotation period of 3 h. Map calculations were performed using a polyhedral gravity model (Werner and Scheeres, 1997) with the radar-derived shape (Nolan et al., 2013) and the Yarkovsky-derived bulk density of 1.26 g cm^{-3} (Chesley et al., 2014). The equatorial ridge (~10% of the total surface area) experiences negative effective gravity because rotational centrifugal forces exceed self-gravity within this region.

101955 Bennu has an equatorial ridge thought to be caused by YORP

Refs: *Nolan et al. 2013 used radar observations to get a shape match, current spin 4.3h period*

* *Equatorial ridges are common to NEAs - grain sizes important to constrain formation mechanisms*

* *The equator of rapidly spinning spheroid is lowest gravitational point and may collect fine grains*

Take away 3. This process may explain asteroid spectral bluing ...

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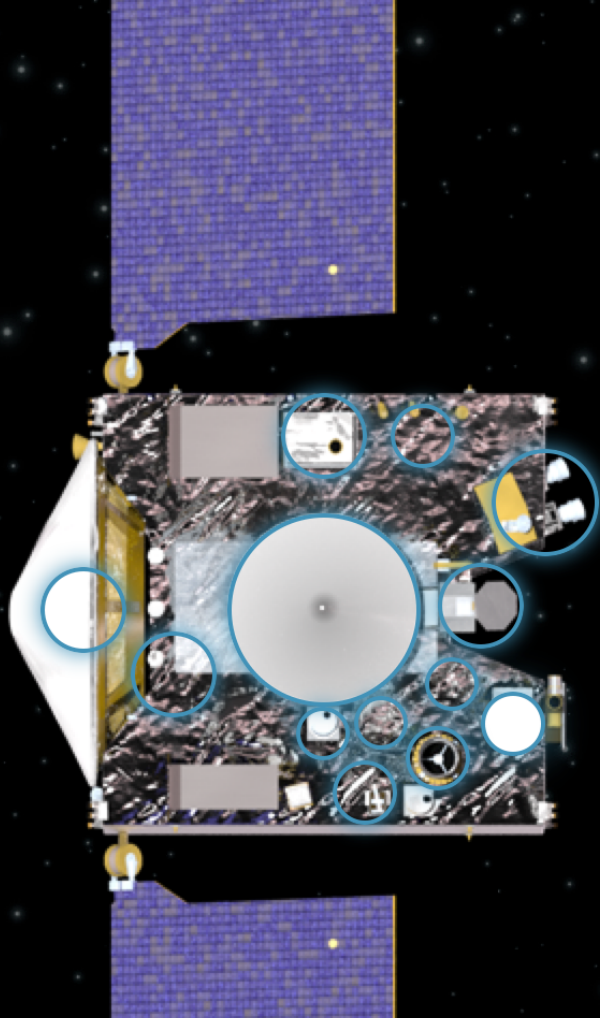

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OVIRS

The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) measures visible and infrared light from Bennu. OVIRS is sensitive from blue through near-infrared wavelengths, spanning 0.4 to 4.3 microns. OVIRS will split the light received from Bennu into its component wavelengths much like a prism can split sunlight into a visible rainbow. Since different chemicals have unique spectral signatures, they can be identified this way. OVIRS will provide spectral maps that identify mineral and organic material globally and of candidate sample sites. It will also gather local spectral information of candidate sample sites.

More Information: Detailed Specifications and Instrument Operations

The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) is a point spectrometer that provides mineral and organic spectral maps and loca spectral information of candidate sample sites. It also provides full asteroid spectral data, global spectral maps (20-m resolution), and spectra of the sample site (0.08–2-m resolution).

OVIRS on OSIRIS-REx - making the hypothesis testable

Refs: www.asteroidmission.org

Have YOU seen spectral bluing in your data?

Please let me know!
Contact abrown@seti.org

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